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DEVELOPMENT OF HIGH-STRENGTH CONCRETE INCORPORATING A LARGE PERCENTAGE OF FLY ASH AND SUPERPLASTICIZERS

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DEVELOPMENT OF HIGH-STRENGTH CONCRETE INCORPORATING A LARGE PERCENTAGE OF FLY ASH AND SUPERPLASTICIZERS

by

P.K. Mukherjee*, M.T. Loughborough** and V.M. Malhotra***

ABSTRACT

This paper reports results of an investigation performed to develop high-strength concrete incorporating superplasticizers and a large percentage of fly ash as replacement for normal portland cement. The concrete mix developed had a water-to-(cement + fly ash) ratio of 0.28, cement and fly ash contents of 390 and 230 kg/m^3 respectively, and a large dosage of a superplasticizer. The 28-day compressive strength of 152 x 305-mm cylinders ranged from 51.0 to 53.8 MPa, and the 28-day flexural strength was in the order of 8 MPa. The drying shrinkage and creep values were comparable to the corresponding values of the reference mix. It was concluded that the concrete developed was satisfactory as regards to both workability and early-age strength, and should find uses in precast concrete operations for the production of high-strength structural units.

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INTRODUCTION

In recent years CANMET has been engaged actively in research in construction materials of mineral origin to conserve energy and resources. A number of research papers have been published on the subject (1,2,3,4), and in 1976 CANMET had sponsored a seminar on Energy and Resource Conservation in the cement and concrete industry (5). One of the less energy-intensive materials which is relatively cheap and easily available is pulverized fuel ash or fly ash. Although fly ash has been used in mass concrete for a long time to save cement and reduce heat of hydration, its use in high-strength structural concrete is of relatively recent origin. In the investigations reported to date on the subject, the fly ash was added not as a replacement but in addition to the portland cement (3). This study was therefore undertaken to determine:

(i) whether high strengths can be achieved with concrete mixes incorporating a large percentage of fly ash as a replacement for portland cement;

(ii) whether strength values achieved in (i) above can be further increased by reducing the water content of the concrete mixes by 20 percent. The loss in slump of the concrete is to be restored by using superplasticizers.

The laboratory work associated with this study was performed at Ontario Hydro Research Laboratories, Toronto, Ontario, under CANMET Contract No. 18.SQ.23440-7-9027.

SCOPE OF INVESTIGATION

The test program consisted of an evaluation of non air-entrained concrete containing Type I portland cement and fly ash in combination with three commercially available superplasticizers. The following series of concrete mixes was made.

(i) Trial mixes - to establish W/C+F* ratio and maximum percentage replacement of cement by fly ash for a reference mix to give a 28-day compressive strength of concrete in the order of 40 MPa;

(ii) Reference mix - to determine the mechanical properties of concrete made using the reference mix;

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* Water-to-(cement + fly ash)

(iii) Water-reduced mixes - to determine the mechanical properties of concrete made by reducing the w/c ratio of the reference mix. The loss in slump of the concrete due to 20 percent water reduction is to be restored using superplasticizers.

MATERIALS USED

Cement and Fly Ash

ASTM Type 1 cement and Ontario hydro fly ash meeting the requirements of ASTM Standard C 618 were used. The physical properties and chemical analysis of the cement and fly ash are given in Tables 1 and 2.

Aggregates

Graded crushed gravel of 20-mm maximum size was used as the coarse aggregate and natural sand was used as the fine aggregate. The relative densities of the coarse and fine aggregates were 2.66 and 2.65 (oven dry) respectively, the corresponding absorption values were 1.10 and 1.37% (ASTM Standards C 127 and C 128).

Superplasticizers

The following three types of superplasticizers were used in the concrete mixes.

(i) Sulphonated melamine formaldehyde condensates (superplasticizer M). It is usually available as a 20% aqueous solution with a density of 1100 kg/m^3 and is limpid (clear) to slightly turbid (milky). The chloride content is negligible.

(ii) Sulphonated naphthalene formaldehyde condensates (superplasticizer N). It is usually available as 42% aqueous solution with a density of 1200 kg/m^3 and is dark brown. The chloride content is negligible.

(iii) Modified naphthalene formaldehyde condensates (superplasticizer L). It is usually available as 20% aqueous solution with a density of 1100 kg/m^3 and is light brown. The chloride content is negligible.

CONCRETE MIXES

A number of trial mixes were made to establish the proportions of the reference mix. The requirements were that the selected mix should contain maximum possible replacement of cement by fly ash and the 28 day compressive strength of 152 x 305-mm cylinders cast from the mix should be in the order of 40 MPa. The concrete mix selected had a W/C+F ratio of 0.35. The portland cement and fly ash contents were 377 and 223 kg/m^3 respectively. The composition of the water-reduced mix was established by reducing the water content of the reference mix by 20 per cent, with slump being maintained the same as for the reference mix by the use of superplasticizers. This resulted in a W/C+F ratio of 0.28 for the water-reduced concrete mix.

The mixing procedure for the concretes was as follows: the coarse and the fine aggregates, the cement and fly ash, and about 60% of the total mixing water were placed in a pan mixer of 0.05-m^3 capacity. The mixer was then started and the ingredients were mixed for 0.5 min. The mixing was continued and the balance of the mixing water, together with the superplasticizers (where used) were added during the next 1.5 min. After all the ingredients were in the mixer, the mixing was done according to ASTM Standard C 192, i.e., the concrete was mixed for 3 min followed by 3 min of rest and 2 min of final mixing.

The properties of the fresh concrete, i.e., slump, density, and air content were determined immediately after the final mixing (Table 3). The tests for the time-of-set of fresh concrete (ASTM C 403) were performed on selected batches of concrete.

PREPARATION AND CASTING OF SPECIMENS

Altogether, there were four mixes, the reference mix and the three containing superplasticizers. Each consisted of four identical batches mixed consecutively. Test cylinders, 152 x 305 mm and prisms 75 x 100 x 406 mm were cast. The details of the specimens cast are given in Table 4. The test specimens were compacted by the standard rodding procedure. The cylinders were cast in sheet metal moulds and the prisms were cast in steel moulds. Creep test specimens were cast in iron moulds and the ends were capped with neat cement paste and scraped to meet the requirements for planeness.

After being moulded, all the specimens were covered with water-saturated burlap and left in the mixing room maintained at 23°C and about 50% relative humidity for 24 h. They were then demoulded and transferred to a standard moist-curing room until required for testing or conditioning.

TESTING OF SPECIMENS

The cylinder and prism specimens were tested in accordance with the schedule shown in Table 4. The test cylinders were capped with a sulphur capping compound on both ends and tested in compression in accordance with ASTM Standard C 39. Prior to the 28-day compressive-strength test, the cylinders were used to determine the chord modulus of elasticity in accordance with ASTM Standard C 469.

The test prisms for shrinkage measurement were removed from the moist-curing room after one day and stored in a room maintained at 23°C and 50% relative humidity for measuring changes in weight and length (ASTM Standard C 157).

All specimens to be used for the creep test were cured in accordance with ASTM Standard C 512, i.e., moist cured for 7 days and thereafter at a temperature of 23°C and a relative humidity of 50%. The creep tests commenced at 28 days. Prior to the testing, gauge points were attached to the creep and control specimens on three gauge lines 120 degrees apart. The creep specimens were loaded in compression to a stress-strength ratio of 0.44 based on the 28-day compressive strength of the companion specimens. Shrinkage strains were measured on the control (unloaded) specimens.

TEST RESULTS AND THEIR ANALYSIS

A total of 72 cylinders and 16 prisms were tested in this investigation. The results of the setting time of fresh concrete are shown in Figure 1. A summary of the strength test results, modulus of elasticity, shrinkage, and creep measurements is given in Tables 5 and 6. Plots of the compressive strength gain versus age, and the total creep strains versus age are shown in Figures 2 and 3.

DISCUSSION OF TEST RESULTS

Mix Proportioning

The reference mix arrived at after trial batches, contained 37% fly ash as a partial replacement for portland cement and met the design stipulation that 152 x 305-mm cylinders cast from this mix attain a 28-day compressive strength in the order of 40 MPa. The use of large percentages of fly ash can result in considerable savings in cement and associated energy costs.

Workability and Time-of-Set of Fresh Concrete

The workability of the reference mix was satisfactory although slightly on the stiff side (Figure 4). The water-reduced, superplasticizers mixes with slumps between 65-75 mm were much more workable but were a bit 'gluey' (Figure 5); however, they seemed satisfactory for precast construction.

The maximum increase in the setting time of concrete incorporating superplasticizers was 3 h (Figure 1).

Compressive and Flexural Strengths

The increases in the compressive and flexural strengths, and in the modulus of elasticity of the water-reduced superplasticized concrete compared with the reference mix (Table 5) can be attributed to the lower W/C+F ratio of the former. The greater degree of hydration caused by the higher dispersion of cement particles under the action of the superplasticizers may have also contributed to improvement in the mechanical properties of the water-reduced concrete mixes.

The laboratory data from other on-going investigations indicate that the 7 and 28-day compressive strength of the reference mix are about 70 and 90% of a comparable mix having a cement content equal to the total cementitious material (600 kg/m^3) used in the reference mix.

The 90-day and later age strengths are likely to be higher for the reference mix than for the mix containing equivalent amount of cement because of the pozzolanic action of the fly ash. The water-reduced reference mix with cement and fly ash content of 390 and 230 kg/m^3 gave 7-day compressive strength in the order of 36 MPa; the 28 and 90-day stengths ranged from 51.0 to 53.8 and 62.5, 74.7 MPa respectively. Thus it is seen that with judicious mix proportioning and use of fly ash, very high strength can be achieved both at early and

later ages with considerable savings in cement. Also, concrete incorporating fly ash will have relatively low heat of hydration. This could be significant for large precast concrete units.

Shrinkage Strains and Moisture Loss

The shrinkage strains and moisture loss of the concretes under investigation have been observed for 448 days (Table 5). The shrinkage of the water-reduced concrete incorporating naphathelene based superplasticizers is comparable to that of the reference concrete whereas the shrinkage of the water-reduced concrete incorporating melamine based superplasticizer is slightly lower than that of the reference concrete. This difference is unexplained. As expected, the moisture loss of the water-reduced superplasticized concrete is lower than that of the reference concrete because the former concretes contain less evaporable water.

Creep Strains

The creep test results (Table 6) show that 560 ± 10 days after loading the water-reduced superplasticized fly ash concrete had higher creep strains than that of the reference fly ash concrete, the difference being in the order of 10%. The creep for the former concrete ranged from 782 to 815 x 10^{-6} mm/mm and the value for the latter concrete was 730 x 10^{-6} mm/mm.

CONCLUDING REMARKS

Satisfactory high strengths can be achieved with concrete incorporating a large percentage of fly ash and superplasticizers.

The mechanical properties of the water-reduced superplasticized fly ash concrete are superior to these of the reference fly ash concrete though the creep strains of the former are somewhat higher. The shrinkage strains of the two types of concrete are comparable.

The workability of the water-reduced, superplasticized fly ash concrete may impose a limitation on its use for cast-in-place construction; however, it appears satisfactory for the production of high-strength structural elements in a precast concrete plant.

Concrete made with combinations of other cements and fly ashes may or may not perform as indicated above.

ACKNOWLEDGEMENT

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Table 1 - Physical properties and chemical analysis of ASTM Type I Cement*

Description of Test	ASTM Type I Cement
Physical tests - general	
Time of set (Vicat needle), h:m	
Initial	2:30
Final	4:20
Fineness: No. 200 (passing), %	97.6
Surface area (Blaine), cm^2/g	3490
Soundness (autoclave), %	0.170
Physical tests - mortar strength	
Compressive strength of 51-mm cubes, MPa	
3-day	20.7
7-day	25.8
28-day	33.4
Chemical analysis, %	
Insoluble residue	. . .
Silicon dioxide (SiO_2)	21.0
Aluminum oxide (Al_2O_3)	5.0
Ferric oxide (Fe_2O_3)	2.4
Calcium oxide (CaO), total	63.2
Magnesium oxide (MgO)	3.1
Sulphur trioxide (SO_3)	2.9
Loss on ignition	1.1
Other	1.3
Compound composition, %	
Tricalcium silicate (C_3S)	52.4
Dicalcium silicate (C_2S)	21.0
Tricalcium aluminate (C_3A)	9.0
Tetracalcium aluminoferrite (C_4AF)	7.0

*Supplied by the manufacturer

Table 2 - Physical properties and chemical analysis of Ontario Hydro fly ash*

Description of Test	Specification Requirements		Test Results
	ASTM C618-78	CSA 266.3M	
Physical Tests			
Relative density	-	-	2.31
Pozzolanic activity index-			
with portland cement, % of control	min 75	min 75	96.3
with lime, 7-day strength, MPa	min 5.5	min 5.5	5.7
Water requirement - % of control	max 105	max 105	100
Increase of drying shrinkage of mortar bars at 28 days, %	max 0.03	max 0.03	- 0.008
**Soundness, autoclave expansion or contraction, %	max 0.5	max 0.5	0.052
**Amount retained when wet sieved on 45 μm sieve, max %	max 34	max 34	11.7
**Multiple factor (product of L.O.I. and fineness, amount retained when wet sieved on 45 μm sieve), max %	max 255	max 225	93
Chemical Tests			
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3), %	min 70.0	-	-
Sulphur trioxide (SO_3), %	max 3.0	max 3.0	1.15
**Available alkalies as Na_2, %	max 1.5	max 1.5	1.02
**Moisture content, %	max 3.0	max 3.0	0.02
**Loss on ignition, %	max 12.0	max 12.0	7.96

* Data supplied by Ontario Hydro

**See applicable specification for exceptions or additional requirements

Table 3 - Proportions and properties of fresh concrete

Mix no.	Batch no.	Mix Proportions, kg/m3						Superplasticizer, % by wt of cement + fly ash	Properties of Fresh Concrete				
		ASTM Type I cement	Ontario Hydro Fly Ash	Fine Aggregate	Coarse Aggregate	Water	W/C+F* ratio		Slump, mm	Entrapped air, %	Temp, °C	Density, kg/m3	Initial time of set, h:m
1	1	377	223	420	1105	208	0.35	-	65	1.5	22	2333	4:40
	2	379	224	420	1107	208	0.35	-	70	1.5	22	2337	
	3	377	223	420	1105	208	0.35	-	65	1.4	22	2333	
	4	377	223	419	1103	208	0.35	-	65	1.4	24	2329	
2	1	389	230	433	1139	171	0.28	M, 1.97	75	1.5	24	2362	4:25
	2	388	230	432	1137	171	0.28	M, 1.97	70	1.7	24	2358	
	3	390	231	434	1141	172	0.28	M, 1.97	65	1.6	24	2367	
	4	389	230	433	1139	171	0.28	M, 1.97	65	1.6	24	2362	
3	1	390	231	434	1141	172	0.28	N, 0.86	70	2.0	24	2367	5:15
	2	391	231	435	1145	172	0.28	N, 0.86	70	1.8	24	2375	
	3	389	230	433	1139	171	0.28	N, 0.86	70	1.9	24	2362	
	4	390	231	434	1143	172	0.28	N, 0.86	70	1.9	24	2371	
4	1	390	231	434	1143	172	0.28	L, 2.70	75	1.6	23	2371	7:40
	2	391	231	435	1145	172	0.28	L, 2.70	75	1.4	24	2375	
	3	390	231	434	1143	172	0.28	L, 2.70	75	1.5	24	2371	
	4	389	230	433	1139	171	0.28	L, 2.70	75	1.6	24	2362	

*Water-to-(cement + fly ash)

Table 4 - Number of test specimens cast from each batch of reference mix and three superplasticized concrete mixes

Tests \ Batch no.	1	2	3	4
No. of cylinders for creep test	1	1	1	-
No. of cylinders for control test (creep)	1	1	1	-
No. of cylinders for 28-day compression test (creep)	1		1	-
No. of cylinders for compression test at:				
7-day	-	1	1	-
28-day	1	1	-	-
56-day	-	1	1	-
91-day	1	1	-	-
183-day	-	-	-	1
365-day	-	-	-	1
No. of prisms for 28-day flexural test	1	-	1	-
No. of prisms for shrinkage test	1	-	1	-
Setting time test	-	-	-	1

NOTE: 1. Number of cylinders per mix = 18
Total number of cylinders for 4 mixes i.e., reference and three superplasticized mixes, 4 x 18 = 72

2. Number of prisms per mix = 5
Total number of prisms = 5 x 4 = 20

3. The cylinders for 28-day compressive strength were used to determine the modulus of elasticity values

Table 5 - Properties of hardened concrete

Mix no.	Batch no.	W/C+F	Type of superplasticizer	Properties of hardened concrete									
				Compressive strength, MPa						Flexural strength, MPa	Modulus of elasticity, at 28-days, MPa x 10^4	Shrinkage measurements		
				7-d	28-d	56-d	91-d	183-d	365-d	28-day		Dry storage, d	Shrinkage, %	Moisture loss, %
1	1	0.35	-	-	41.0	-	51.8	-		6.3	3.17	448	-0.0441	-1.83
	2	0.35	-	28.8	37.9	51.9	51.5	-		-	3.43		-	-
	3	0.35	-	25.0	-	41.4	-	-		6.8	-		-0.0453	-1.84
	4	0.35	-	-	-	-	-	53.4	57.3	-	-		-	-
2	1	0.28	M	-	53.3	-	65.2	-		8.3	3.48	448	-0.0413	-1.19
	2	0.28	M	36.1	52.5	61.8	65.6	-		-	3.46		-	-
	3	0.28	M	36.1	-	57.7	-	-		8.0	-		-0.0399	-1.13
	4	0.28	M	-	-	-	-	70.0	69.8	-	-		-	-
3	1	0.28	N	-	52.5	-	66.9	-		8.0	3.48	448	-0.0467	-1.07
	2	0.28	N	36.8	53.8	61.7	67.1	-		-	3.46		-	-
	3	0.28	N	36.8	-	63.2	-	-		7.4	-		-0.0427	-1.08
	4	0.28	N	-	-	-	-	66.3	74.7	-	-		-	-
4	1	0.28	L	-	51.0	-	62.7	-		7.8	3.45	448	-0.0455	-1.19
	2	0.28	L	35.4	51.0	59.5	62.5	-		-	3.47		-	-
	3	0.28	L	34.1	-	59.0	-	-		8.1	-		-0.0451	-1.26
	4	0.28	L	-	-	-	-	63.4	62.5	-	-		-	-

Note: All test results are for individual specimens only

Table 6 - Properties of hardened concrete - creep measurements

Mix no.	f'_c at 28-days, MPa	Stress applied MPa	Stress/Strength ratio	Total creep strain mm/mm x 10^{-6}	
				370 days	560 ± 10 days
1	38.7	15.4	0.4	699	730
2	52.5	20.9	0.4	748	789
3	53.9	21.5	0.4	761	782
4	49.9	19.8	0.4	786	815

Notes:

1. Test cylinders were cast in a vertical position.
2. Test cylinders were moist-cured for 7 days followed by 21 days of curing at 50% RH and 73°F and then loaded at 28 days in a room maintained at 50% RH and 73°F.
3. Strain measurements were made using a 100 mm Pfender gauge.
4. Three cylinders from each mix (one from each of the first three batches) were loaded in one frame and the creep values shown are the average for three cylinders.
5. Two cylinders from each mix (one each from batches 1 and 3) were tested in compression at 28 days.

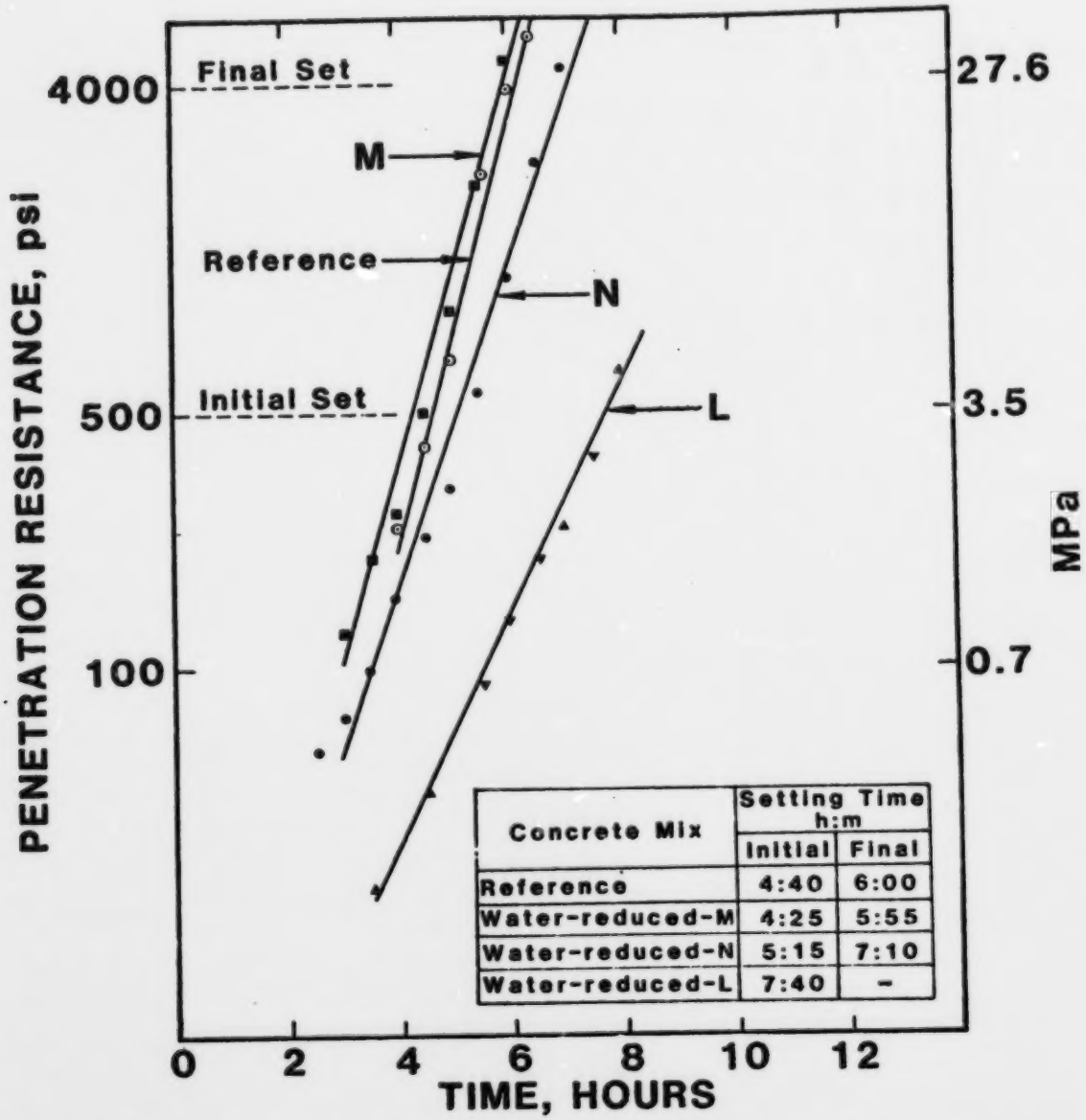


Fig. 1 - Setting-time characteristics of the reference and water-reduced, superplasticized concretes.

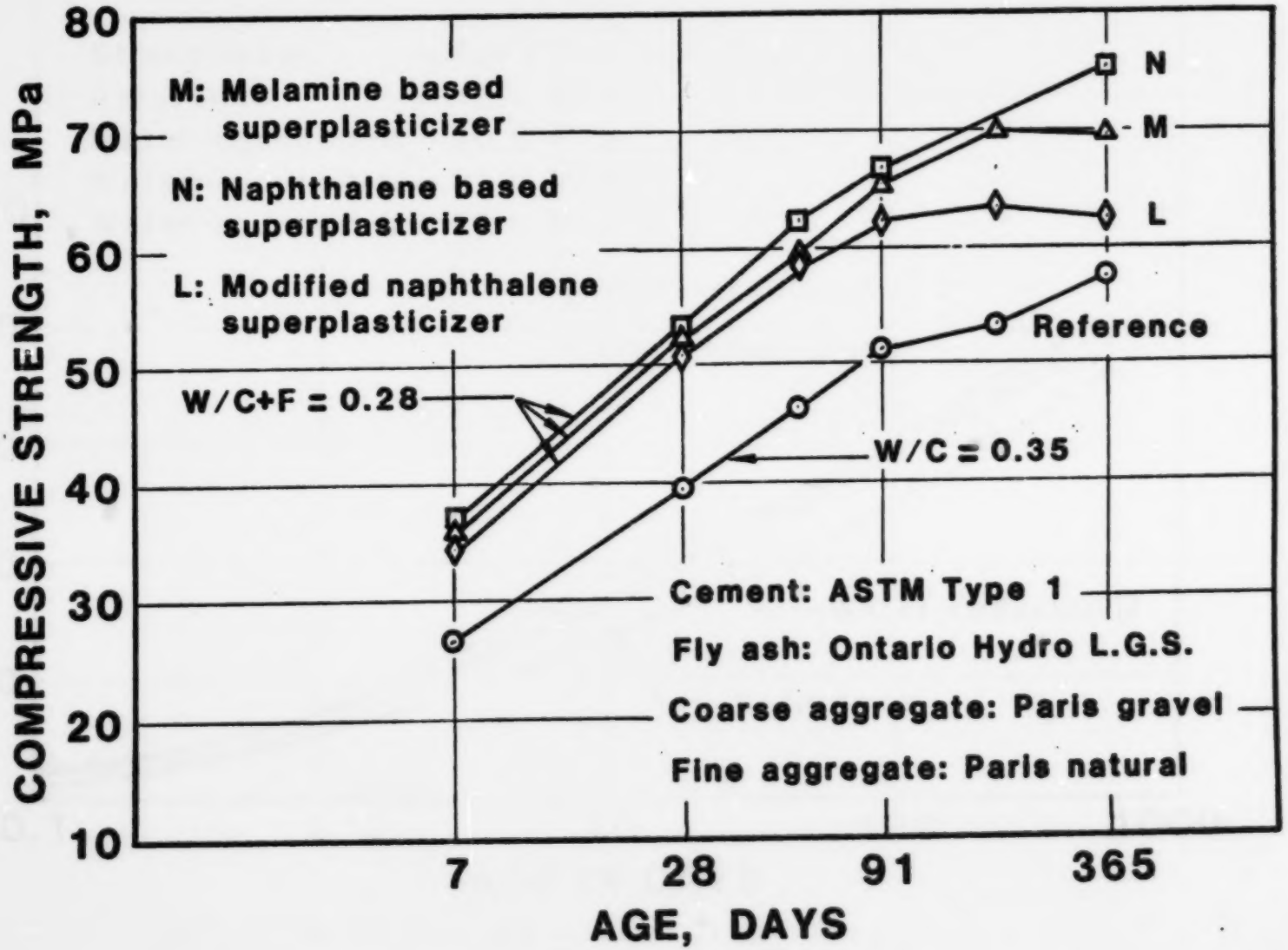


Fig. 2 - Compressive strength versus age of the reference, and water-reduced, superplasticized concretes.

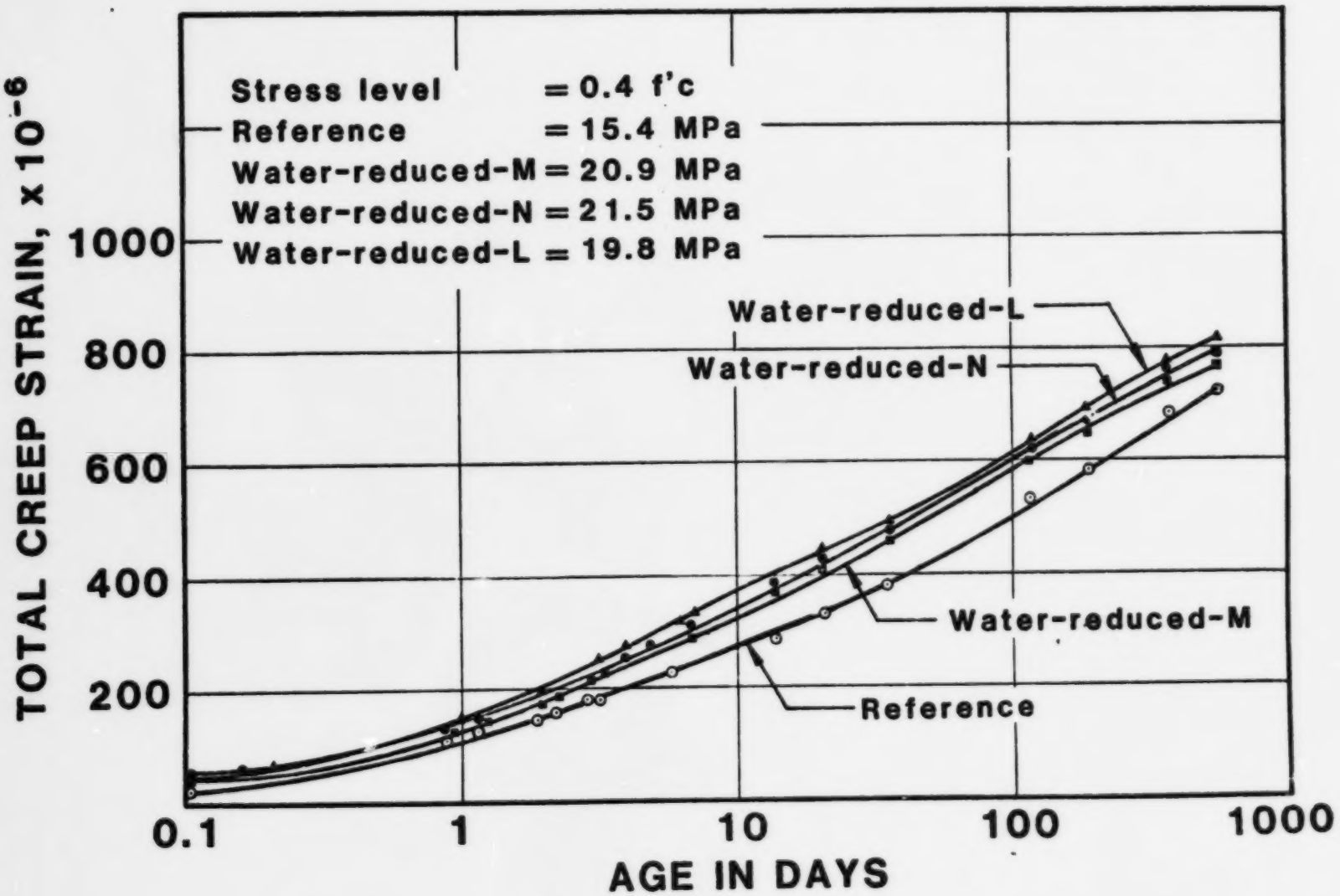
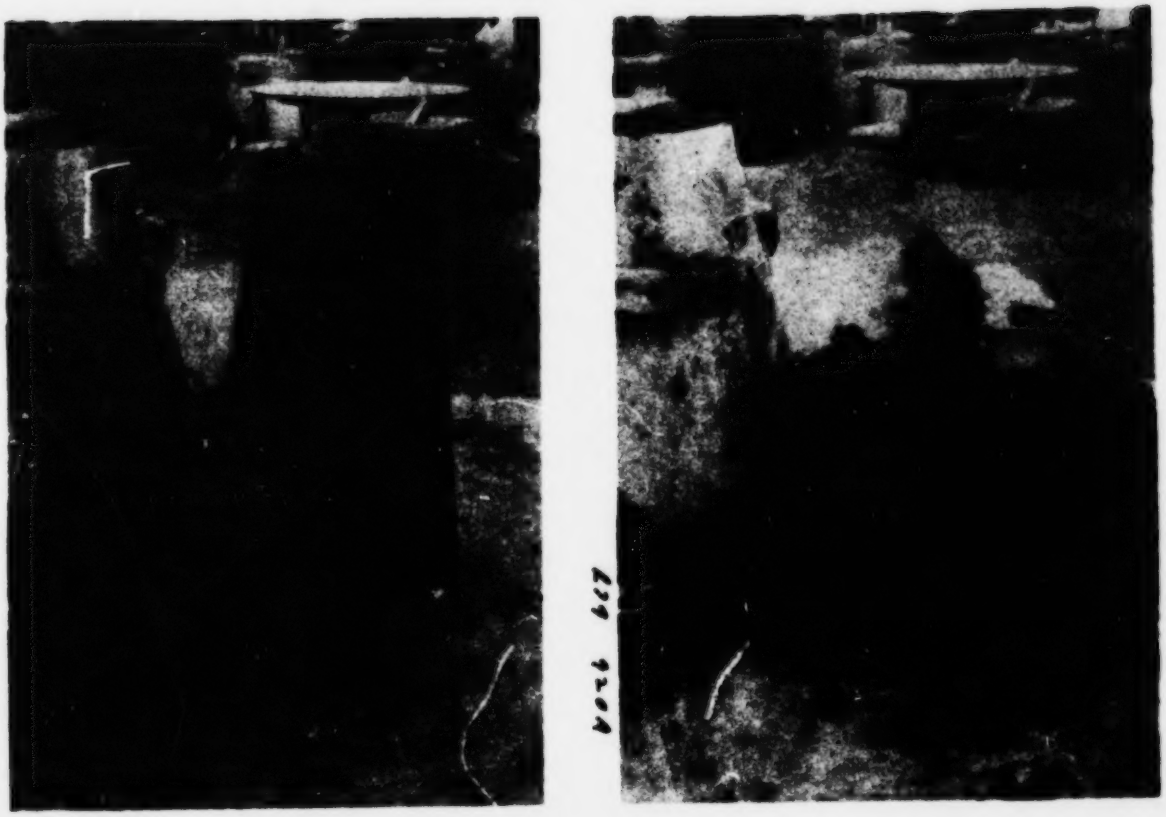


Fig. 3 - Total creep strain versus age



(a) (b)

Fig. 4 - Water-reduced reference concrete mix (Note poor workability of concrete mix).

(a) immediately after slump test

(b) after tapping with a slump rod

(a) (b)

Fig. 5 - Water reduced reference concrete mix after the addition of a superplasticizer (Note change in workability of concrete)

(a) immediately after slump test

(b) after tapping with a slump rod

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